

GRB 060121: IMPLICATIONS OF A SHORT/INTERMEDIATE DURATION γ -RAY BURST AT HIGH REDSHIFT

A. DE UGARTE POSTIGO¹, A.J. CASTRO-TIRADO¹, S. GUZIY^{1,2}, J. GOROSABEL¹, G. JÓHANNESSON³, M.A. ALOY^{4,5}, S. MCBREEN⁶, D.Q. LAMB⁷, N. BENITEZ¹, M. JELÍNEK¹, S.B. PANDEY¹, D. COE¹, M. D. PÉREZ-RAMÍREZ⁸, F.J. ACEITUNO¹, M. ALISES⁹, J.A. ACOSTA-PULIDO¹⁰, G. GÓMEZ¹⁰, R. LÓPEZ¹¹, T.Q. DONAGHY⁷, Y.E. NAKAGAWA¹², T. SAKAMOTO¹³, G.R. RICKER¹⁴, F.R. HEARTY¹⁵, M. BAYLISS⁷, G. GYUK⁷ AND D. G. YORK⁷

ABSTRACT

Since the discovery of the first short-hard γ -ray burst afterglows in 2005, the handful of observed events have been found to be embedded in nearby ($z < 1$), bright underlying galaxies. We present multiwavelength observations of the short-duration burst GRB 060121, which is the first observed to clearly outshine its host galaxy (by a factor $> 10^2$). A photometric redshift for this event places the progenitor at a most probable redshift of $z = 4.6$, with a less probable scenario of $z = 1.7$. In either case, GRB 060121 could be the farthestmost short-duration GRB detected to date and implies an isotropic-equivalent energy release in gamma-rays comparable to that seen in long-duration bursts. We discuss the implications of the released energy on the nature of the progenitor. These results suggest that GRB 060121 may belong to a family of energetic short-duration events, lying at $z > 1$ and whose optical afterglows would outshine their host galaxies, unlike the first short-duration GRBs observed in 2005. The possibility of GRB 060121 being an intermediate duration burst is also discussed.

Subject headings: gamma rays: bursts; gamma-ray bursts: individual (GRB 060121)

1. INTRODUCTION

Since 1993 γ -ray bursts (GRBs) have been classified into two subgroups according to the observed duration and hardness-ratio derived from their gamma-ray spectra: short-hard (SGRB) and long-soft (LGRB) events (Kouveliotou et al. 1993).

The first X-ray detections of SGRB afterglows by *Swift* (Gehrels et al. 2005) and *HETE-2* (Hjorth et al. 2005; Villasenor et al. 2005) in combination with optical and radio detections have suggested that they release less energy than the LGRBs (Fox et al. 2005) ($E_\gamma(\text{SGRB}) \sim$

10^{49} erg vs. $E_\gamma(\text{LGRB}) \sim 10^{51}$ erg) and that they may originate from the coalescence of neutron star (NS) or NS-black hole (BH) binaries at cosmological distances. Until GRB 060121, the detected optical afterglows of SGRBs have been comparable in brightness to their host galaxies or dimmer, unlike the case of long-soft bursts that may outshine their hosts by a factor of up to $\sim 10^6$ (van Paradijs et al. 2000). The distance scale is also considered to be different, having all short bursts with definite redshifts been $z_{\text{SGRB}} < 0.6^{\dagger}$ while long bursts show a broader range, mainly between 0.5 and 5, with $< z_{\text{LGRB}} > \sim 1.8$.

2. OBSERVATIONS AND DATA REDUCTION

GRB 060121 was detected at 22:24:54.50 UT on 21 January 2006 by FREGATE, WXM and SXC instruments aboard the *HETE-2* mission (Arimoto et al. 2006). The position of the gamma-ray event was distributed using the GRB Coordinates Network (GCN) 13 s later. The spectral peak energy $E_p = 120 \pm 7$ keV (Boer et al. 2006), together with a duration of 1.97 ± 0.06 s initially classified it in the SGRB group of events (Fig. 1). It was also observed by Konus/*WIND* (Golenetskii et al. 2006a) and followed up by *Swift*/XRT (Mangano et al. 2006), whose observations substantially improved the initial 28' *HETE-2* error box radius and helped to identify the optical counterpart (Malesani et al. 2006).

On receipt of the initial alert by *HETE-2*, a mosaic of images was triggered at the 1.5 m telescope of Observatorio de Sierra Nevada (OSN) in order to map the entire error box. The first detection of the afterglow was obtained only 22 minutes after the γ -ray event. Complementary observations were requested with the 2.2

¹ Instituto de Astrofísica de Andalucía (IAA-CSIC), Camino Bajo de Huétor, 50, E-18008 Granada, Spain.

² Nikolaev State University, Nikolska 24, 54030 Nikolaev, Ukraine.

³ Science Institute, University of Iceland, Dunhaga 3, IS-107 Reykjavik, Iceland.

⁴ Max-Planck-Institut für Astrophysik, D-85741, Garching bei München, Germany.

⁵ Departamento de Astronomía y Astrofísica, Universidad de Valencia, E-46100 Burjassot, Spain.

⁶ Max-Planck-Institut für extraterrestrische Physik, D-85748 Garching bei München, Germany.

⁷ Department of Astronomy and Astrophysics, University of Chicago, Chicago, Illinois 60637, U.S.A.

⁸ Dpto. de Física (EPS), Universidad de Jaén, E-23071 Jaén, Spain.

⁹ Calar Alto Observatory, Apartado de Correos 511, E-04080 Almería, Spain.

¹⁰ Instituto de Astrofísica de Canarias, Vía Láctea s/n, E-38200 La Laguna - Tenerife, Spain.

¹¹ Departament d'Astronomia i Meteorologia, Universitat de Barcelona, Av. Diagonal 647, E-08028 Barcelona, Spain.

¹² Department of Physics and Mathematics, Aoyama Gakuin University, Fuchinobe 5-10-1, Sagami-hara, Kanagawa 229-8558, Japan.

¹³ NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, U.S.A.

¹⁴ MIT Kavli Institute, Massachusetts Institute of Technology, 70 Vassar Street, Cambridge, Massachusetts 02139, U.S.A.

¹⁵ Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80303 U.S.A.

[†] We point out that there is still an ongoing debate about the redshift of GRB 050813, which could lie at a redshift of $z \sim 1.8$ (Berger 2006), although no optical or radio counterpart was found to support this scenario.

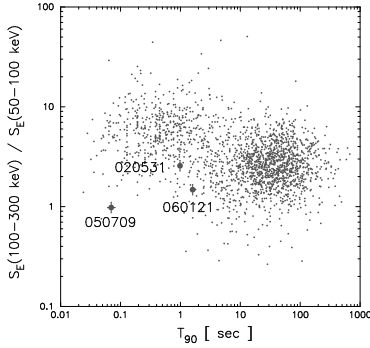


FIG. 1.— Burst duration vs. spectral hardness diagram. Large black circles are the locations of the three currently established *HETE-2* short GRBs superimposed on the distribution of 1973 BATSE short and long GRBs (small grey dots).

TABLE 1
OBSERVATIONS OF THE AFTERGLOW OF GRB 060121

Mean Date (Jan 2006)	Band	Tel.	Int. time (s)	Flux (μ Jy)
22.2443	K	4.2mWHT	750	17.1 ± 1.4
23.2402	K	4.2mWHT	1000	6.3 ± 1.6
23.3308	K	3.5mARC	3600	7.48 ± 0.65
27.2588	K	3.5mARC	3600	< 2.13
21.9495	I	1.5mOSN	120	19.3 ± 4.4
21.9633	I	1.5mOSN	120	10.0 ± 2.8
22.0458	I	1.5mOSN	300	10.8 ± 2.5
22.1162	I	1.5mOSN	6×300	4.55 ± 0.83
22.2539	I	1.5mOSN	5×300	< 2.5
22.0493	R	2.2mCAHA	600	3.70 ± 0.97
22.0963	R	2.2mCAHA	2×600	1.14 ± 0.33
22.1590	R	2.2mCAHA	2×600	1.23 ± 0.49
22.2385	R	2.2mCAHA	3×600	1.35 ± 0.37
23.1828	R	1.5mOSN	12×900	< 0.8
24.0804	R	2.2mCAHA	6×900	0.55 ± 0.14
22.0885	V	2.2mCAHA	2×600	< 1.1
22.1952	V	2.2mCAHA	5×600	< 0.7
22.0336	B	2.2mCAHA	600	< 1.7
22.1560	B	2.2mCAHA	7×600	< 0.9
22.0258	U	2.2mCAHA	600	< 3.3
22.1200	U	2.2mCAHA	5×600	< 2.1

m telescope of the German-Spanish Calar Alto Observatory (CAHA), the 4.2 m William Herschel telescope (WHT) at Roque de los Muchachos Observatory and the 3.5 m Astrophysical Research Consortium (ARC) telescope at Apache Point Observatory. Equatorial coordinates of the optical near-infrared (nIR) afterglow yielded: R.A.(J2000)= $09^h09^m52^s.02$, Dec.(J2000)= $+45^\circ39'45''.9$ ($0''.5$ uncertainty at 1σ level).

Optical images have been photometrically calibrated against Sloan Digital Sky Survey (Adelman-McCarthy et al. 2006) applying the corresponding transformations (Jester et al. 2005) for our photometric system. For nIR images we have used field stars from the 2 Micron All Sky Survey catalogue (Skrutskie et al. 2006). A Galactic extinction (Schlegel et al. 1998) correction of $E(B-V)=0.014$ is applied and magnitudes have been converted to flux density units (Jy) for clarity (Fukugita et al. 1995; Cox 2000). The photometric data are displayed in Table 1.

The X-ray light curve and spectrum were obtained from the *Swift*/XRT data. The spectrum was fitted with a power-law plus a fixed Galactic hydrogen col-

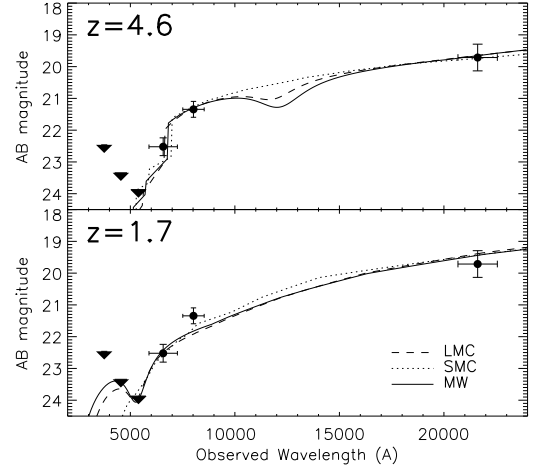


FIG. 2.— Spectral flux distribution. A fit of the data points with an extinguished power law and a Lyman- α break returns two peaks of probability. The main one, covering a probability of 63% is centred at $z = 4.6$ with rest frame extinction of $A_V = 0.3 \pm 0.2$ (top) and the secondary with an 35% is centred at $z = 1.7$ with $A_V = 1.1 \pm 0.2$ (bottom).

umn density ($N_{H(\text{Gal})} = 1.7 \times 10^{20} \text{ cm}^{-2}$) and an intrinsic column density $N_{H(\text{int})}$ at a varying redshift in the range $0.1 \leq z \leq 6.0$. A spectral index ($F \sim \nu^{-\beta}$) of $\beta = 1.10^{+0.17}_{-0.16}$ ($\chi^2/d.o.f. = 36/29$) was derived from the fit with an intrinsic column density that, depending on the selected redshift scenario, ranges from $N_{H(z=1.5)} = 0.39^{+0.17}_{-0.20} \times 10^{22} \text{ cm}^{-2}$ to $N_{H(z=4.6)} = 2.9^{+1.3}_{-1.5} \times 10^{22} \text{ cm}^{-2}$.

3. RESULTS

The detections in I, R and K bands and the upper limits imposed for the U, B and V bands, allowed us to construct a spectral flux distribution (SFD) at a mean epoch of 2.5 hours after the burst (Fig. 2). The nIR K band point is extrapolated from a near epoch using as reference a quasi-simultaneous R passband detection. The data were fit with a power law spectrum, a superposed intrinsic extinction (Pei 1992) and a Lyman- α blanketing model (Madau 1995) at a varying redshift. The slope of the powerlaw was chosen to be $\beta_{\text{opt}} = 0.60 \pm 0.09$, as derived from the X-ray spectra, assuming $\nu_{\text{opt}} < \nu_c < \nu_X$ at a pre-break epoch, following the standard fireball model prescription (Sari et al. 1999). This is confirmed by the modelling described below. We obtained two probability peaks in our redshift study. The main one (with a 63% likelihood) places the burst at $z = 4.6 \pm 0.5$ with an intrinsic extinction of $A_V = 0.3 \pm 0.2$ magnitudes. A secondary peak (with a 35% likelihood) would imply that the afterglow lies at a $z = 1.7 \pm 0.4$ and $A_V = 1.4 \pm 0.4$ magnitudes. In either case, GRB 060121 is the farthest short duration GRB detected to date. A redshift of $z < 0.5$ has a likelihood $\leq 0.5\%$ and implies extinctions $A_V > 2.0$. Adopting a flat cosmology with $\Omega_\Lambda = 0.73$, $\Omega_M = 0.27$ and $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and considering a γ -ray fluence of $4.71^{+0.44}_{-0.31} \times 10^{-6} \text{ erg cm}^{-2}$, we obtain an isotropic-equivalent energy release in γ -rays of $E_{\gamma, \text{iso}} = 2.18^{+0.21}_{-1.72} \times 10^{53} \text{ erg}$ ($E_{\gamma, \text{iso}} = 4.30^{+0.40}_{-2.63} \times 10^{52} \text{ erg}$) for a redshift of $z = 4.6$ (1.7), 2(1) orders of magnitude higher than other $E_{\gamma, \text{iso}}$ values determined for previous SGRBs (Table 2). This is comparable to the values measured for LGRBs (Frail et al. 2001).

We have modelled the GRB 060121 afterglow follow-

TABLE 2
PHYSICAL PROPERTIES OF THE SHORT γ -RAY BURSTS DETECTED TO DATE

GRB	Redshift z	T_{90} (s)	Fluence (erg cm $^{-2}$)	$E_{\gamma,iso}$ (erg)	L_X (erg s $^{-1}$)	$F_{A/G}$
050509B	0.225	0.04	9.5×10^{-9}	4.5×10^{48}	$< 7 \times 10^{41}$	< 0.005
050709	0.160	0.07	2.9×10^{-7}	6.9×10^{49}	3×10^{42}	~ 1.0
050724	0.258	3.00	6.3×10^{-7}	4.0×10^{50}	8×10^{43}	~ 0.2
050813 †	0.722/1.8?	0.60	1.2×10^{-7}	6.5×10^{50}	9×10^{43}	< 0.15
051221A	0.546	1.40	3.2×10^{-6}	2.4×10^{51}	6×10^{44}	~ 1.0
060121	1.5	1.97	4.7×10^{-6}	2.9×10^{52}	8×10^{45}	~ 20.0
	4.6			2.1×10^{53}	6×10^{46}	
060313	≤ 1.7	0.70	1.4×10^{-5}	$\leq 1 \times 10^{53}$	-	> 3.0

NOTE. — The table displays, in columns: Name of the burst, redshift, duration of the gamma ray emission, measured gamma-ray fluence, isotropic-equivalent γ -ray energy, isotropic-equivalent luminosity observed in X-rays 10 hours after the burst and the fraction of afterglow flux 12 hours after the burst and the host galaxy flux (both in R band). The compilation is based on this work and Fox et al. (2005); Schady & Pagani (2006); Golenetskii et al. (2006b); Soderberg et al. (2006) and references therein. GRB 050813 values are calculated for $z=0.722$.

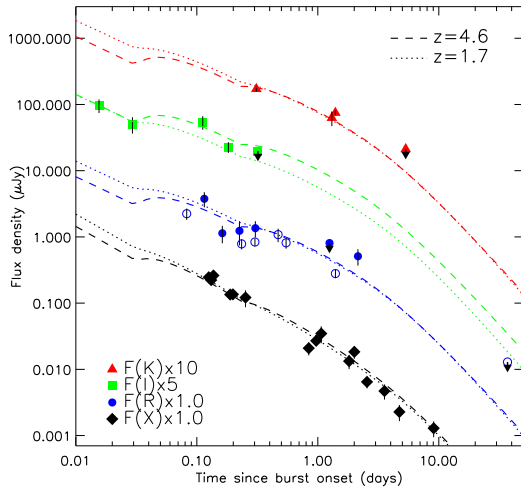


FIG. 3.— Light curve of the afterglow in the near infrared (K), visible (R & I) and X-ray bands. The figure shows the result of the fit of the model in the most probable high- z (4.6) case which has been optimized with values of $p = 2.06$, $\theta_0 = 0.6^\circ$ and $n = 0.1$ cm $^{-3}$ and in the low- z (1.5) case, which gives a slightly worse fit with $p = 2.05$, $\theta_0 = 2.3^\circ$ and $n = 0.04$ cm $^{-3}$. Filled symbols are data presented in this article whereas empty ones are data from the literature.

ing the prescription of Jóhannesson et al. (2006) on the basis of the standard fireball model for which 2 energy injections have been included at 0.035 and 0.23 days after the onset of the burst. These energy injections are required in order to explain the bumpy behaviour seen during the first hours (Fig. 3); similar features have been seen in long GRB light curves (Castro-Tirado et al. 2006) at $z \sim 4$. The model has been fitted for both $z = 4.6$ and $z = 1.7$ scenarios with slightly better results for the high- z case. Independent on the redshift, the multiwavelength model points to a narrow jet with half opening angle $\theta_0 < 10^\circ$ in a low density environment (10^{-3} cm $^{-3} \leq n \leq 0.1$ cm $^{-3}$; the lower density limit fits the observations better for the case where the GRB took place at $z = 4.6$ while the upper density value accommodates better the data at $z = 1.7$), with efficiencies of conversion of kinetic to gamma-ray energy $\eta_\gamma < 0.05$.

4. DISCUSSION

GRB 060121 has a T_{90} duration of 1.97 ± 0.06 s in the 85-400 keV energy band and a hardness ratio (HR) $S_E(100-300 \text{ keV})/S_E(50-100 \text{ keV}) = 1.48 \pm 0.18$. We

note that the intrinsic duration of GRB 060121 would be 1.6 s with HR of 1.7 if placed at $z \sim 0.2$ (similar to GRB 050709), 0.7 s and 3.3 (if $z = 1.7$) or 0.4 s and 4.6 (if $z = 4.6$). We have studied the classification of the progenitor of this GRB (as "old" or "young") considering eight criteria: (a) duration, (b) pulse widths, (c) spectral hardness, (d) spectral lag, (e) energy radiated in γ -rays, (f) existence of a long, soft bump following the burst, (g) location of the burst in the galaxy and (h) the type of host galaxy. Four (a, e, f, g) criteria provide strong evidence that GRB 060121 had an "old" progenitor, while four (b, c, d, h) are inconclusive. Thus, we can make a strong claim, although not conclusive, that GRB 060121 had an "old" progenitor. Further details on this analysis are given in Donaghy et al. (2006).

If we consider the progenitor to be a merger of compact objects (Eichler et al. 1989; Aloy et al. 2005), the released energy needs either a large conversion efficiency of the accreted mass into neutrino emission ($\gtrsim 0.05$), a large accretion disk mass ($\gtrsim 0.1 M_\odot$) or an appropriate combination of both factors (Oechslin & Janka 2006). Considering a merger at a redshift $z > 1.5$, there is a higher consistency with the theoretical models where the rate of NS+NS or NS+BH mergers follows the star formation rate with delays of ~ 1 Gyr (Janka et al. 2005) than with those of very old populations of NS+NS progenitor systems (Nakar et al. 2005). Furthermore, the high extinction derived from the SFD fit indicates that the merger probably took place within the galaxy rather than in the outer halo or intergalactic medium and thus, the system received a small natal kick, although the density of the local event environment is relatively low ($n \sim 0.1$ cm $^{-3}$) as indicated by the afterglow fits discussed here. Alternatively, if the energy was extracted via a Blandford-Znajek process (Blandford & Znajek 1977), either the value of the dimensionless angular momentum of the central BH is $a > 0.3$, the magnetic field surrounding the BH is $B \gtrsim 10^{16}$ G or the BH has a mass larger than $3 M_\odot$ (or a combination of these parameters).

Late observations by the *Hubble Space Telescope* (HST) have shown no trace of the afterglow down to magnitude $R \sim 28$ about 37 days after the burst but do show an underlying galaxy (Levan et al. 2006). We estimate the probability of finding such a galaxy within the $0.5''$ radius error box (derived from our astrometry) as 1.3×10^{-2} following Piro et al. (2002). A chance association is unlikely but not completely negligible. We have reanalyzed

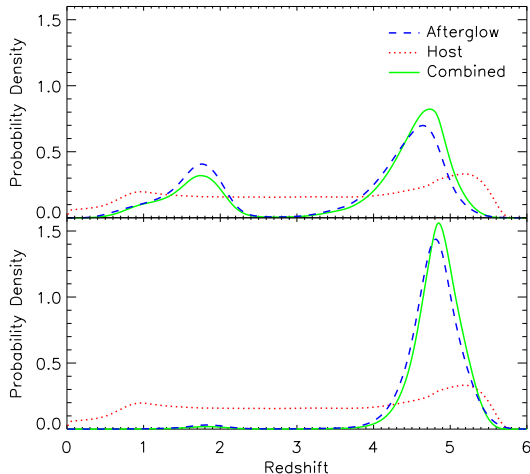


FIG. 4.— Probability distribution vs. redshift. The top panel shows the probability distribution for the GRB afterglow, the host galaxy and a combination of both which favours the high redshift scenario. In the bottom panel we have used an extinction-based prior which cancels the low redshift peak.

the photometry of the galaxy using ColorPro (Coe et al. 2006) obtaining $F606W_{AB} = 27.35 \pm 0.16$ (*HST* wide band filter centred at 606 nm) and $F160W_{AB} = 24.05 \pm 0.38$ (*HST* wide band filter centred at 1600 nm). Although the information is very limited we have used this photometry to study the probability distribution for the redshift of the galaxy using a bayesian photometric redshift as described by Benítez (2000); Benítez et al. (2004). We obtain two peaks of probability at $z = 1.0$ and $z = 5.2$, the latter being more probable. By multiplying this probability by the one obtained for the afterglow we can assign a probability of 70% for the higher redshift case and a

28% for the lower redshift scenario (see Fig. 4). Applying a prior based on well determined extinctions for LGRBs (Kann et al. 2006) the likelihood of a high redshift event would rise to 98%. This is a soft constrain as it favours low extinctions, like it could be expected from the low density derived from our model.

5. CONCLUSION

These results suggest that assuming that GRB 060121 were a SGRB, there exists an emerging population of short events located at high redshifts and with energies comparable to those of long events. In this group we may also include GRB 060313 (Schady & Pagani 2006) or GRB 000301C (Jensen et al. 2001). This population would produce afterglows which significantly outshine their host galaxies, with isotropic energy releases of $E_{\gamma,iso} \sim 10^{52-53}$ erg similar to the values observed in long events. Furthermore, following the classification by Horváth et al. (2006) GRB 060121 could be classified in the intermediate group (Horváth 1998; Balastegui et al. 2001) of events with a 68% probability (28% for short-burst and 4% for long-burst). The relationship between this second population of short bursts and the intermediate population of GRBs will be determined or excluded by future observations.

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